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A redescription of the poorly known cave millipede *Skleroprotopus membranipedalis* Zhang, 1985 (Diplopoda, Julida, Mongoliulidae), with an overview of the genus *Skleroprotopus* Attems, 1901

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Abstract

We redescribe the poorly known Chinese millipede *Skleroprotopus membranipedalis* Zhang, 1985 recorded from Shi-Hua (Stone Flower) Cave, Fangshan County, Beijing. The species' original description is in Chinese in an obscure outlet which significantly hampers its recognition from its congeners. Here, based on newly collected material, we provide the first scanning electron micrographs of important taxonomic traits. In addition to its type locality, we report the species also from Yun-Shui (Cloud Water) Cave, situated in the same county, some 18 km away. We propose the genus *Senbutudoiulus* Miyosi, 1957 to be a junior subjective synonym of *Skleroprotopus* Attems, 1901, **syn. n.**, and introduce the following new combination: *Skleroprotopus platypodus* (Miyosi, 1957), **comb. n.** (former *Senbutudoiulus*).

Keywords

China, new record, new synonymy, troglobiomorphism

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Introduction

The eastern Asian julidan family Mongoliulidae is currently known to comprise 8 genera and 36 species, as recently reviewed by Enghoff et al. (2017). Twenty of these species are described under *Skleroprotopus* Attems, 1901 making it by far the largest genus within the family, with a distribution range including northeastern China, the Russian Far East (Primorskiy Province), the Korean Peninsula, and Japan (see Fig. 1). Many *Skleroprotopus* species are supposed local endemics known only from their original descriptions. This is indeed the case with *S. membranipedalis* Zhang, 1985 described from Shi-Hua (Stone Flower) Cave, Fangshan County, Beijing, the original description of which is in Chinese, with rather crude line drawings which hamper its recognition. The species is of a particular interest as it stands out from its congeners with its troglobiomorphic habitus.

We here provide an emended description of *S. membranipedalis* based on both recently collected topotypic material and specimens from the Cloud Water Cave (new record), and present a brief overview of the genus *Skleroprotopus*.

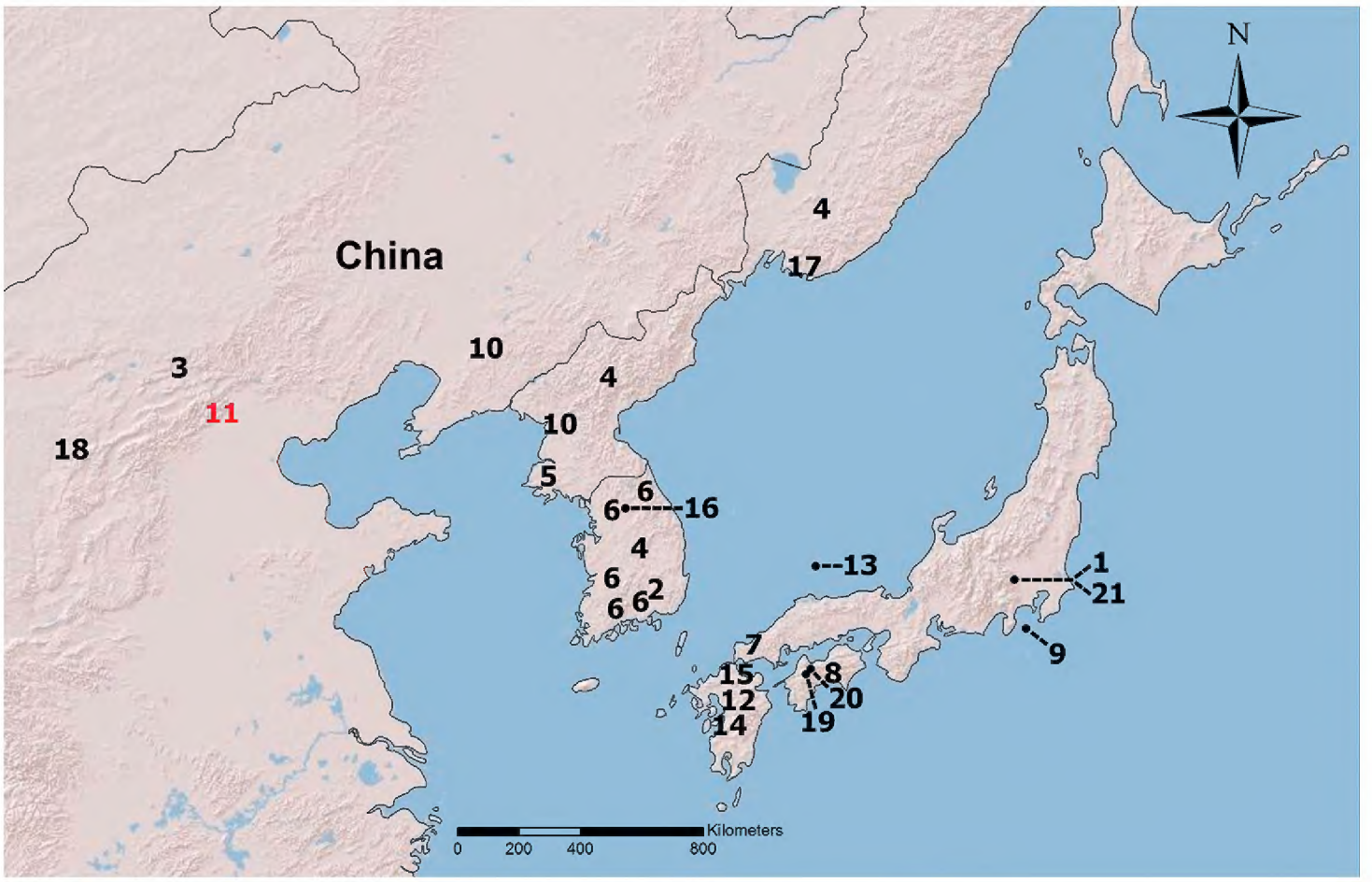


Figure 1. Summarized distribution map of species of *Skleroprotopus*. **Numbers: 1** *Skleroprotopus chichibuensis* Shinohara, 1960 **2** *S. chollus* Mikhaljova & Korsós 2003 **3** *S. confucius* Attems, 1901 **4** *S. coreanus* (Pocock, 1895) **5** *S. costatus* Mikhaljova & Korsós, 2003 **6** *S. hakui* Takakuwa, 1940 **7** *S. ikedai* Takakuwa, 1941 **8** *S. inferus* Verhoeff, 1939 **9** *S. insularum* Verhoeff, 1939 **10** *S. laticoxalis* Takakuwa, 1942 **11** *S. membranipedalis* Zhang, 1985 **12** *S. montanus* Takakuwa, 1942 **13** *S. okiensis* Takakuwa, 1941 **14** *S. osedoensis* Miyosi, 1957 **15** *S. platypodus* (Miyosi, 1957) **16** *S. ramuliferus* Lim & Mikhaljova, 2000 **17** *S. schmidti* Golovatch, 1979 **18** *S. serratus* Takakuwa & Takashima, 1949 **19** *S. sidegatakedensis* Miyosi 1957 **20** *S. simplex* Takakuwa, 1941 **21** *S. toriii* Takakuwa, 1940.

Description of the sampling sites

Shi-Hua (Stone Flower) Cave

Shi-Hua Cave, also known as Qian-Zhen Cave and Shi-Fo Cave, is located on the south bank of Da-Shi River in Fang-Shan Mountain, Fang-Shan World Geological park, approximately 50 km southwest of Beijing. It is the largest limestone cave in northern China, and the one with the richest deposits of secondary carbonate sediments. The cave is locally important in both touristic and scientific aspects. It is part of the Shi-Hua Karst system formed by several caves, namely Ji-Mao, Yin-Hu, Shi-Hua, Qing-Feng and Kong-Shui, connected by an underground river (Lü et al. 2010).

Shi-Hua is a multilayer limestone cave consisting of 7 levels interconnected by numerous passages and chambers, measuring a total length of about 5640 m. The cave's highest point measured from the entrance is 14 m and the lowest is 158 m (Liu et al. 2015). Its stratum originates from sea deposits formed 400 MYA (Lü 2007). The actual formation of the cave started in the Neogene (23MYA), with the dissolving of the carbonatite (Lü et al. 2010).

Yun-Shui (Cloud Water) Cave

Yun-Shui Cave is also situated in Fang-Shan World Geological park, 75 km from Beijing and some 18 km in a straight line from Shi-Hua Cave. Yun-Shui comprises several halls with a total length of about 610 m. Despite the proximity to Shi-Hua, Yun-Shui, along with the caves San-Qing, Long-Xian-Gong and Xian-Xia, is part of a different karst system – the Tanghsien Karst system located on the northern bank of Ju-Ma River. The two systems – Tanghsien and Shi-Hua – are not connected by underground rivers or terrestrial channels.

The stratum of Yun-Shui was developed from epicontinental sea deposits 1000 MYA, and, similar to Shi-Hua, the cave itself was shaped during the Neogene (Lü 2007). The stalactites of Yun-Shui were formed after the Medio-Pleistocene (Lü 2007, Lü et al. 2010).

Material and methods

The material was collected in November 2013 by Pavel Stoev, Christo Deltshev and Shuqiang Li. It is deposited in the Myriapod collection of the National Museum of Natural History, Sofia (NMNHS). The scanning electron micrographs were obtained with the aid of a JEOL JSM-5510 at the Faculty of Chemistry, Sofia University. The examined body parts were mounted on cover glasses equipped with a sticky tape, and sputter-coated with gold-palladium. The states of the taxonomic characters presented in Table 1 were extracted from the original descriptions and drawings of the corresponding species, and from the few subsequent taxonomic treatments of certain species.

Taxonomic part

Genus *Skleroprotopus* Attems, 1901
***Mongoliulus* Pocock, 1903**
***Paraprotopus* Verhoeff, 1939**
***Nesoprotopus* Verhoeff, 1939**

***Senbutudoiulus* Miyosi, 1957 syn. n.**

Diagnosis. A genus of Mongoliulidae, most similar to the genus *Ansiulus* Takakuwa, both sharing a number of characters such as: ozopores in all body-rings, an anterior gonopod with an unsegmented telopodite (except for *S. schmidti*) and a slightly to considerably higher coxite carrying a well-developed flagellum, and a bifid (except for *S. simplex*) posterior gonopod consisting of a slender solenomerital process and a broader, shield-like, apically setose, caudal process. Differs from *Ansiulus* mostly by the complete absence of telopodites on posterior gonopods and by the strongly reduced telopodites of male leg-pair 7 (except for *S. sidegatakedensis*).

***Skleroprotopus membranipedalis* Zhang, 1985**

Skleroprotopus membranipedalis Zhang, 1985: 154–156, figs 1–8.

Material. 3 males, 7 females & 16 juv., China, Beijing, Fangshan Distr., Shi-Hua (Stone Flower/ Stone Buddha) Cave (type locality), 39°47'36.7"N, 115°56'32.1"E, 12.XI.2013, P. Stoev, Ch. Delchev & S. Li leg. (NMNHS); 7 females & 14 juv., same Distr., Mt. Shangfang, Yun-Shui (Cloud Water) Cave, the touristic part, 39°40'29"N, 115°48'35"E, 3.XI.2013, under stones, creeping on walls, humid clay, some 100 m from the entrance, same collectors (NMNHS).

Diagnosis. Differs from congeners mostly by the flattened, blade-like, basolateral process on the caudal face of the anterior gonopod, and by the completely pigmentless ocelli.

Redescription. Measurements: males 49–51 mm in length, 2.5–2.6 mm in height at mid-body, body ring formula 62+(1–2)+T; females 49–60 mm, 2.4–2.8 mm, and (61–67)+(1–2)+T, respectively.

Colouration in life (Fig. 2): light brown-beige, head whitish; metazonites with darker, narrow, concentric bands, passing just behind the ozopores; repugnatorial glands reddish-brown in living specimens, becoming brown-greyish in ethanol.

General morphology: Adults with 25–40 very small and completely pigmentless ocelli arranged in a narrow triangular field; eye rows unclear. Vertigial setae and pits absent; 4 supralabral and 22–28 labral setae. Antennae (Fig. 3) slender, 1.4–1.5 times as long as head; antennomere 3 longest, ca. twice as long as 6; 2, 4 and 5 subequal in length; 5 and 6 insignificantly thicker than the previous three, their distal margins with a dense whorl of minute sensilla basiconica. Mandibles with 7 pectinate lamellae. Gnathochilar-

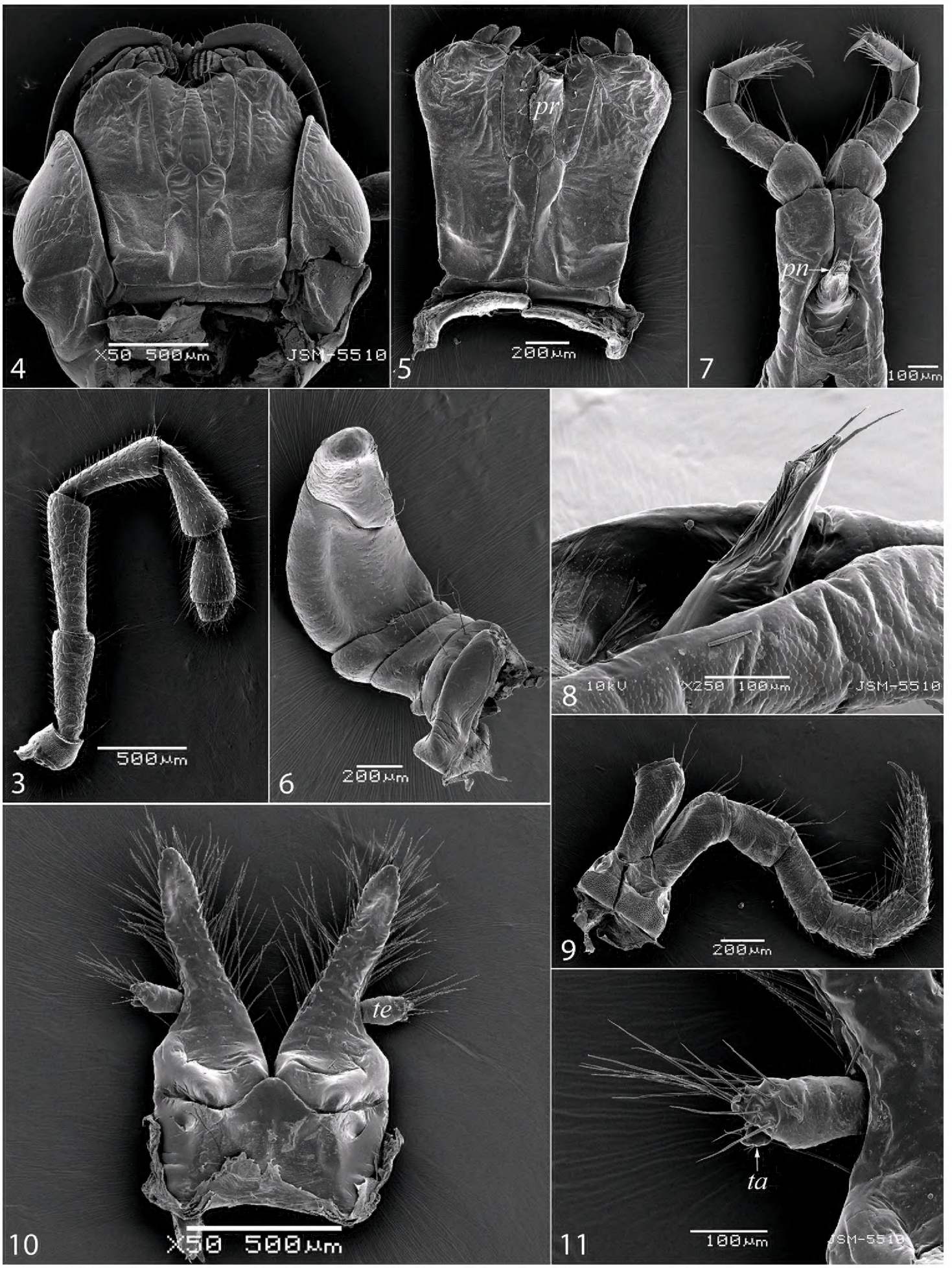
Figure 2. Living specimens of *Skleroprotopus membranipedalis* in Shi-Hua Cave.

ium (Figs 4, 5) with only three apical setae on each stipes and with 7–8 setae on each lamella lingualis arranged in a L-shaped row; prementum of an elongated pentagonal shape, just slightly longer than lamellae linguales, completely separating them.

Collum with ca. 10 shallow striae on each side. Body rings considerably vaulted, this becoming increasingly pronounced towards telson. Prozonites with several shallow, somewhat undulating, transverse striae encircling them (striae being more pronounced dorsally), and dense, short and shallow, longitudinal striation on dorsum near the pro-metazonital suture. Metazonites with rather sparse and shallow (deeper ventrally) longitudinal striae, these disappearing above the ozopore level; without setae on hind margins. Ozopores relatively small, set far behind the pro-metazonital suture, at ca. metazonital mid-length.

Epiproct very short and blunt in both sexes, marginally with one to several setae. Hypoproct broad and short, nearly semi-elliptic, edentate, tightly fitting under the paraprocts; its margin slightly more strongly vaulted in males. Paraprocts with only 2–3 setae each situated near the caudal margins. Walking legs slender; tarsi of mid-body legs 2–2.3 times longer than tibiae, and 3.3–3.7 times longer than the apical claw.

Male sexual characters: Male mandibular stipites enlarged, ventrally incised, forming two nearly equal, subconical lobes. Prementum (***pr*** in Fig. 5) of gnathochilarium distally swollen. Leg-pair 1 (Fig. 6) massive, six-segmented, strongly compressed dorsoventrally, reaching up to distal margin of gnathochilarium, without any remnant of an apical claw; podomere 5 very large, strongly arched dorsad, approx. as long as the basal one; podomeres 2–4 each with several long setae in a transverse row, 5 and 6 medially with numerous minute setae. Leg-pair 2 (Fig. 7) with massive, robust coxae, fused to



Figures 3–11. *Skleroprotopus membranipedalis*, external morphology: **3** male antenna **4** female head, ventral view **5** male gnathochilarium, ventral view **6** left male leg 1, latero-dorsal view **7** male leg-pair 2 with penis, caudal view **8** penis *in situ*, lateral view **9** left male leg 3, caudal view **10** male leg-pair 7, caudal view **11** telopodite of male leg 7, caudal view. **Symbols:** ***pn***: penis, ***ta***: tarsal remnant with apical claw, ***te***: telopodite.

each other, basally forming a deep sinus for the penis. Penis (Fig. 8 & ***pn*** in Fig. 7) elongated, membranous, dorso-medially with an oval groove, and with two long apical setae. All walking legs (Fig. 9) without adhesive pads or other modifications. Pleurotergite 7 ventrally forming small, rounded protrusions originating entirely from the metazonite, directed mesad. Leg-pair 7 (Fig. 10) modified to elongated, non-segmented, leaf-like coxites, proximally with rather small, non-segmented telopodites (Fig. 11 & ***te*** in Fig. 10), the latter with a minute subapical remnant of a tarsus (***ta***) bearing a claw.

Gonopods (Figs 12–16): *in situ* jutting out of the gonopodal sinus, distal parts of posterior gonopods partly concealed by the anterior gonopods laterally.

Anterior gonopod (Figs 12, 13) with an elongated coxite, gradually narrowing towards a rounded apex, with several setae medially on caudal face; coxite bearing a large, flattened axe blade-like process (***b***), emerging subbasally from its lateral margin, directed caudo-distad, and a well-developed telopodite (***te***), almost half as long as the coxite, non-segmented, apically setose, laterobasally with a minute remnant of a second podomere (***r***). Flagellum (***f***) ca. as long as the coxite, distally densely microsetose, giving it a brush-like appearance; tip not branched.

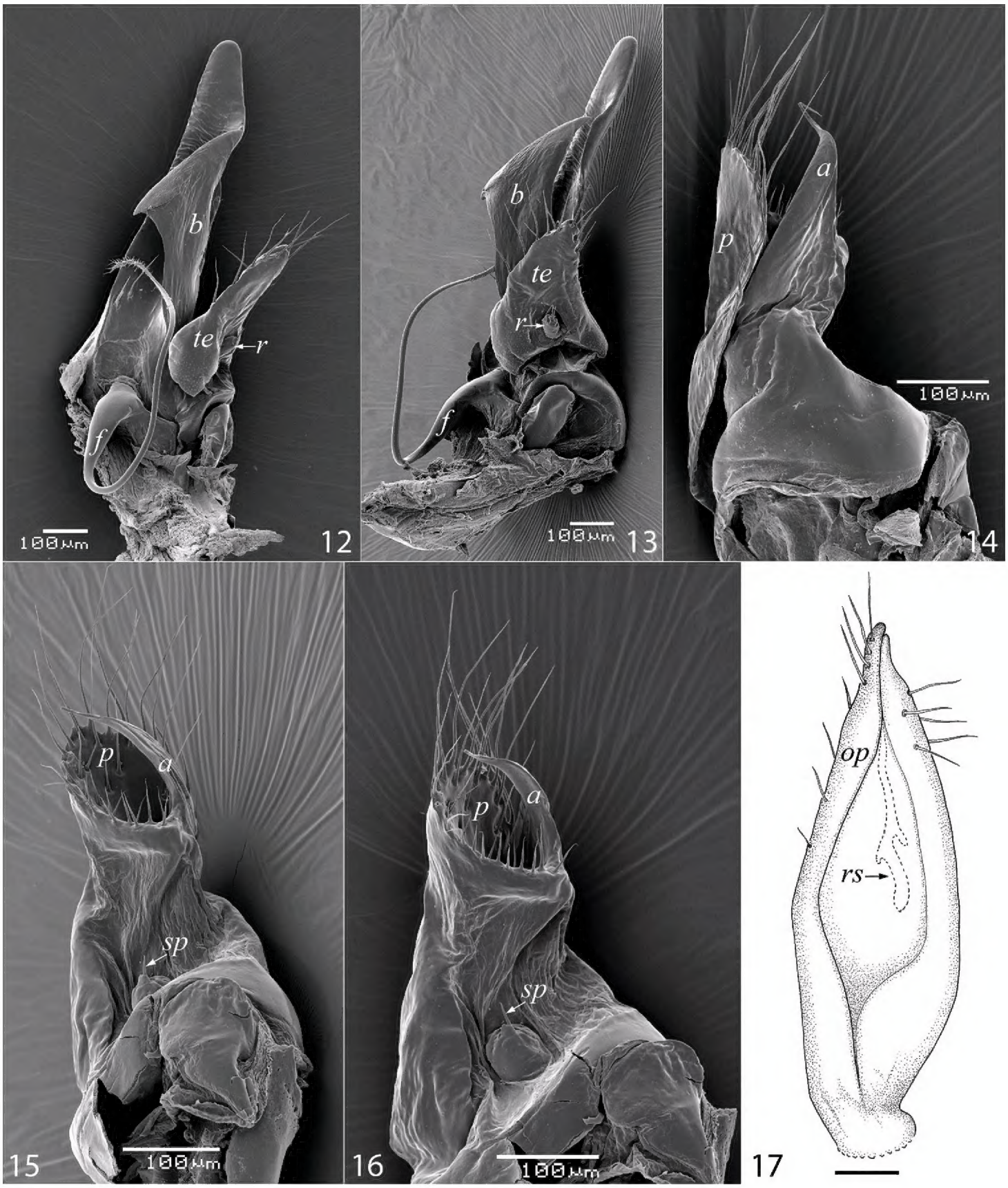
Posterior gonopod (Figs 14–16) stout, with a massive base, distally divided in two parts: a broad, shield-like posterior process (***p***), marginally and disto-frontally bearing long setae; and a simple, unipartite anterior process (***a***), gradually narrowing towards a fine, somewhat bent, filiform apex; mesobasal hump bearing a short spine (***sp***).

Female sexual characters: Leg-pair 1 somewhat thicker and shorter, leg-pair 2 also shorter, but not thicker than the following legs. Vulva (Fig. 17) elongated, subconical; operculum (***op***) slightly higher than bursa, both rather sparsely setose; receptaculum seminis (***rs***) rather small compared to overall size of vulva, in shape of a simple tube, with some very short, pocket-like branches.

Remarks. With its light coloration, slender legs and antennae, and pigmentless ocelli *S. membranipedalis* seems to be the most troglobiomorphic species within the genus (see e.g. Liu et al. 2017). Of the remaining six species occurring in caves, namely *S. ikedai*, *S.inferus*, *S. osedoensis*, *S. platypodus*, *S. sidegatakedensis*, and *S. toriii*, only *S. sidegatakedensis* and *S. ikedai* display similarly light-colored bodies, and all possess blackish ocelli, except for *S. ikedai* and *S. platypodus*, for which this feature is unknown.

However, the presence of ocelli in *S. membranipedalis* suggests a still ongoing adaptation towards troglobiism, meaning that the species has entered the underground relatively recently, possibly in the Pleistocene, in response to the increasingly cooler and drier climate and the gradual replacement of forests by grasslands in the temperate zones – the so called "climatic relict hypothesis" as a model of subterranean colonization (Culver and Pipan 2009). This makes sense also in the light of the rather young geological age of the caves Shi-Hua and Yun-Shui (see introduction part).

Apart from its troglobiomorphic alterations, *S. membranipedalis* is morphologically most similar to *S. coreanus* and *S. serratus*, with whom it shares the lack of claws in the male first legs, the elongated coxites of male 7th legs, the apically non-branched fla-



Figures 12–17. *Skleroprotopus membranipedalis*, gonopods and vulva: **12** left anterior gonopods, caudal, slightly lateral view **13** left anterior gonopod, lateral view **14** left posterior gonopod, lateral view **15** right posterior gonopod, antero-mesal view **16** same, mesal view **17** left vulva, lateral view. **Symbols:** ***a***: anterior process, ***b***: axe blade-like process, ***f***: flagellum, ***op***: operculum, ***p***: posterior process, ***r***: remnant of a podomere; ***rs***: receptaculum seminis, , ***sp***: basal spine, ***te***: telopodite. Scale bar (**17**): 0.2 mm.

gellum, and the well-divided posterior gonopod. On the other hand, its six-segmented male first legs suggest a proximity to *S. hakui*, but this is in contradiction with the apically bifurcated flagellum in the latter species.

Discussion

Miyosi (1957a) erected the genus *Senbutudoiulus* with a sole species *S. platypodus* Miyosi, 1957, based on several characters distinguishing it from the morphologically similar *Skleroprotopus*, in particular: the strongly flattened male leg-pair 1, being almost equally broad until the penultimate podomere, and the slightly flattened leg-pair 2; mandibles with more than six pectinate lamellae, and gnathochilarium with an oval prementum. However, none of these characters can reliably define a genus for the following reasons:

1. Considering the great interspecific variations of the male leg-pair 1 in *Skleroprotopus*, including important features such as the number of podomeres or presence vs. absence of apical claws, their shape observed in the sole species of *Senbutudoiulus* – *S. platypodus* Miyosi, 1957 – is not sufficiently unusual to justify a separate genus.
2. With the exception of *S. montanus*, the number of the mandibular pectinate lamellae exceeds 6 also in those species of *Skleroprotopus* for which this character is known, namely in *S. confucius* (the type species), *S. membranipedalis*, *S. schmidti*, *S. hakui*, and *S. toriii*, all showing 7 lamellae.
3. A similar oblong oval shape of the gnathochilarium is also observed in members of *Skleroprotopus*, such as *S. coreanus*.
4. The slightly unusual shape of the male leg-pair 2 is too weak for a main generic diagnostic character.

It is also noteworthy that the opisthomerite in *Senbutudoiulus platypodus* is conspicuously similar to that in *Skleroprotopus osedoensis* Miyosi, 1957, described from a cave in the same Japanese prefecture as the former species (Miyosi 1957a). The similarity and possible synonymy of *Senbutudoiulus* with *Skleroprotopus* was already suggested by Golovatch (1979), although not formalized.

Thus, we here propose a new synonymy: *Senbutudoiulus* Miyosi, 1957 = *Skleroprotopus* Attems, 1901, syn. n., and a new combination: *Skleroprotopus platypodus* (Miyosi, 1957), comb. n.

Of the remaining mongoliulid genera, *Ansiulus* Takakuwa, 1940 is conspicuously similar to *Skleroprotopus*, and is a possible synonym of the latter, as already pointed out by Mikhaljova (2004). However, the most important diagnostic character of *Ansiulus*, namely the presence of a telopodital remnant at the base of the opisthomerite (Takakuwa 1940b), is so far unknown in members of *Skleroprotopus*, and seemingly distinguishes the genus well. Even though, some uncertainties about the exact species composition of *Skleroprotopus* still remain, mostly concerning the allocation of *S. sidegatakedensis*. The male 7th legs in this species have a remarkably similar conformation to that shown by males of *Ansiulus aberrans* Mikhaljova & Korsós, 2003. Moreover, the unknown posterior gonopods in the former species could possibly possess telopodital remnants – the other character distinguishing *Ansiulus* from *Skleroprotopus*.

Table 1. Main diagnostic characters of species of *Skleroprotopus*. Symbols: * - divided apically; ** - completely undivided.

	Number of articles of male leg-pair 1	Claws on male leg-pair 1	Number of articles of telopodites of male leg-pair 7	Coxites of male leg-pair 7	Promerital telopodites	Flagellum apically	Opisthomerite deeply divided into 2 branches	Sources
S. chichibuensis	5	absent	3	massive, stout	~ 1/2 as long as coxites	bifurcated	yes	Shinohara 1960
S. chollus	5	absent	1	very short and stout	~ 1/2 as long as coxites	bifurcated	yes	Mikhaljova and Korsós 2003
S. confucius	5	absent	3	rather slender	~ 2/3 as long as coxites	bifurcated	yes	Attems 1901
S. coreanus	5	absent	3	long and slender	~ 3/4 as long as coxites	non-branched	yes	Golovatch 1979; Mikhaljova 2004
S. costatus	5	absent	1	rather slender	~ 2/3 as long as coxites	non-branched	no*	Mikhaljova and Korsós 2003
S. hakui	6	absent	1–2	long and slender	~ 3/4 as long as coxites	bifurcated	yes	Takakuwa 1940a
S. ikedai	7	absent	2	somewhat elongated	~ 2/3 as long as coxites	bifurcated	yes	Takakuwa 1941
S. inferus	5	present	2	massive, stout	~ 2/3 as long as coxites	bifurcated	yes	Verhoeff 1939
S. insularum	3	absent	1	massive, stout	~ 2/3 as long as coxites	?	?	Verhoeff 1939
S. laticoxalis	5	absent	3	very short and stout	~ 1/2 as long as coxites	bifurcated	yes	Takakuwa 1942
S. membranipedalis	6	absent	2, the 2nd one minute	long and slender	~ 1/2 as long as coxites	non-branched	yes	Zhang 1985; pers. obs.
S. montanus	5	absent	3	rather short and stout	almost as long as coxites	?	yes	Takakuwa 1942
S. okiensis	5	absent	2	massive, stout	~ 2/3 as long as coxites	bifurcated	yes	Takakuwa 1941
S. osedoensis	5	absent	1	short and stout	~ 1/4 as long as coxites	bifurcated	yes	Miyosi 1957a
S. platypodus	5	absent	2	short and stout	~ 1/4 as long as coxites	bifurcated	yes	Miyosi 1957a
S. ramuliferus	5	absent	2	massive, somewhat elongated	~ 2/3 as long as coxites	non-branched	yes	Lim and Mikhaljova 2001; Mikhaljova and Korsós 2003
S. schmidti	5	present	2	somewhat elongated	~ 3/4 as long as coxites	non-branched	yes	Golovatch 1979
S. serratus	5	absent	1–3	long and slender	almost as long as coxites	non-branched	yes	Takakuwa and Takashima 1949
S. sidegatakedensis	5	present	2, both very large	short and stout	~ 1/2 as long as coxites	bifurcated	?	Miyosi 1957b
S. simplex	5	absent	2, the 2nd one minute	somewhat elongated	~ 2/3 as long as coxites	non-branched	no**	Takakuwa 1941
S. toriii	5	absent	2, both very short	massive, rather short	~ 2/3 as long as coxites	bifurcated	yes	Takakuwa 1940a

In general, the distribution of the main taxonomic characters within *Skleroprotopus* is mosaic-like, as it can be traced in Table 1. The presence of morphologically isolated species, like *S. insularum* having 3-segmented male first legs, *S. schmidti* showing segmented promerital telopodites, and *S. sidegatakedensis* with conspicuously large telopodites of male legs 7, presents a further obstacle for a possible intrageneric division. Such has been applied only by Verhoeff (1939) who recognized three subgenera: *Skleroprotopus* s. str., *Paraprotopus* Verhoeff and *Nesoprotopus* Verhoeff, the latter two monotypic. And while *Nesoprotopus* diserves a special attention in respect to the outstanding morphology of its sole species, *S. insularum*, the males of which have 3-segmented legs 1, *Paraprotopus* can hardly be used today, as the two characters that distinguish it from the nominotypical subgenus – a bifurcated vs. an unipartite flagellum and male 2nd coxae fused vs. these being divided, respectively – have their states rather randomly distributed among species of the genus. Besides this, certain species (e.g. *S. hakui* and *S. toriii*) show only partial fusion of the coxae which reduces further the diagnostic value of this character.

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